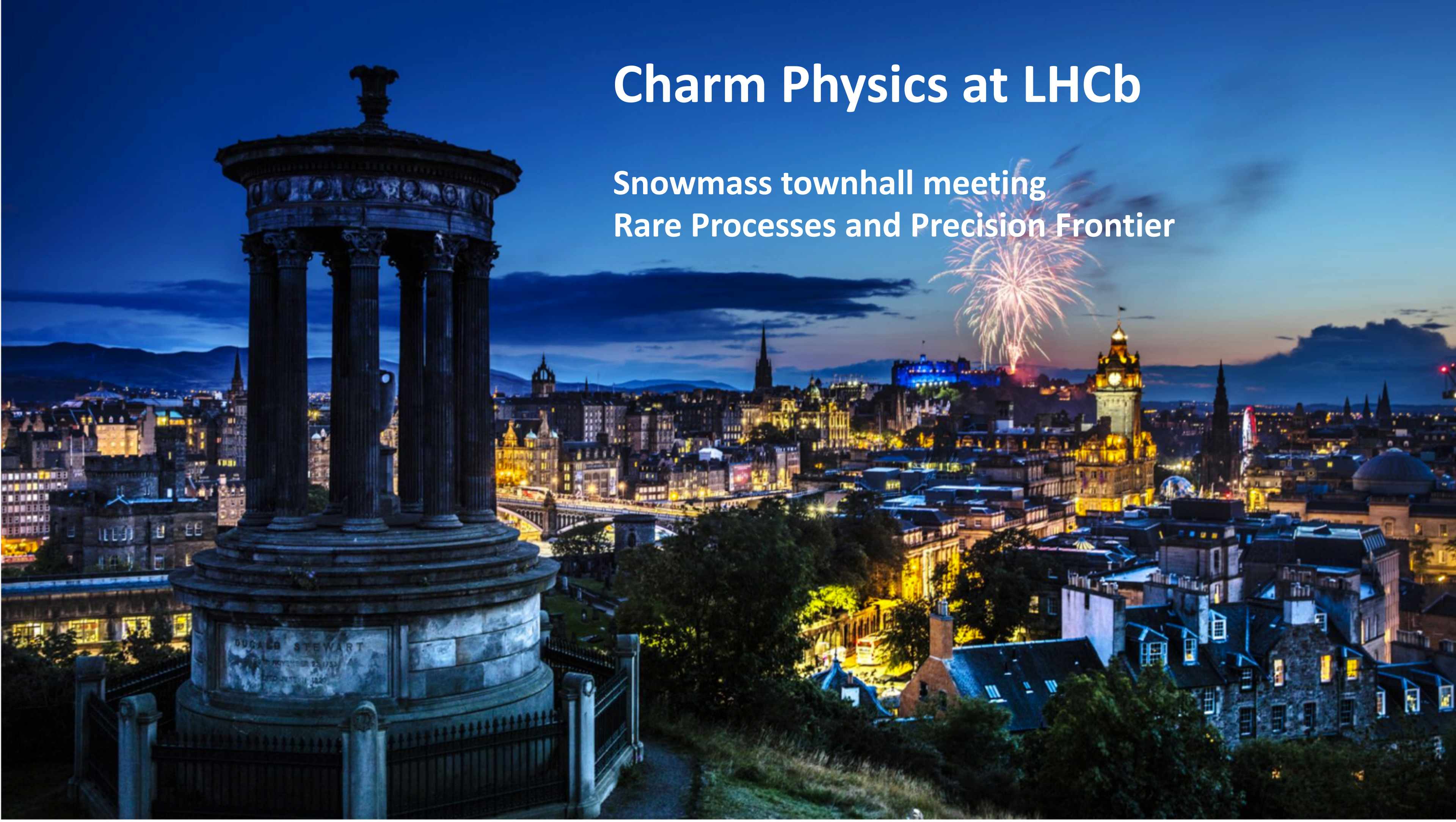


Charm Physics at LHCb

Snowmass townhall meeting
Rare Processes and Precision Frontier

Mark Williams

2nd October 2020

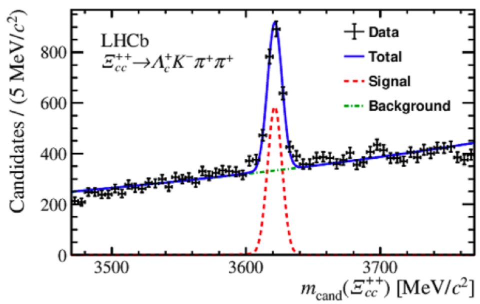
THE UNIVERSITY of EDINBURGH

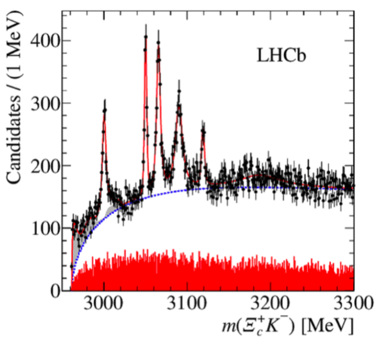
THE ROYAL SOCIETY

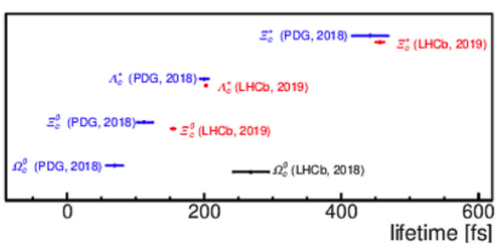
LHCb

Charm @LHCb: A broad programme

Spectroscopy, production, & properties







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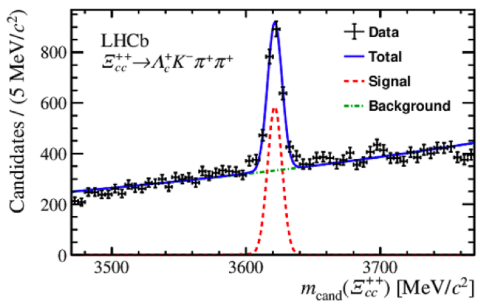
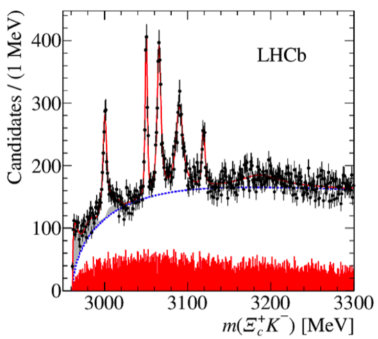
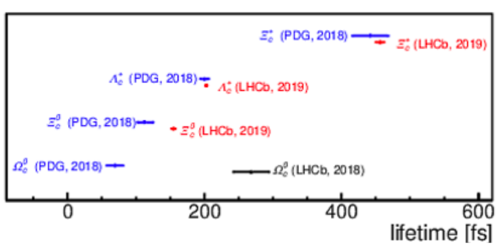
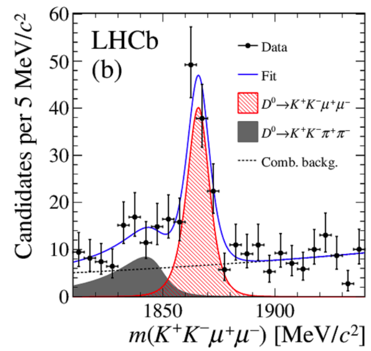
Spectroscopy, production, & properties

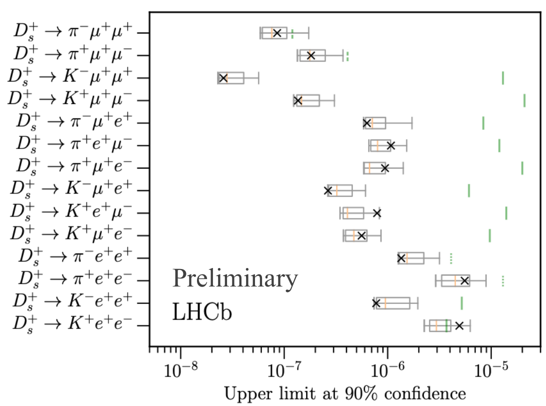






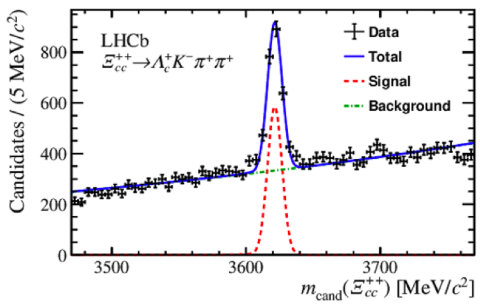
Rare charm decays

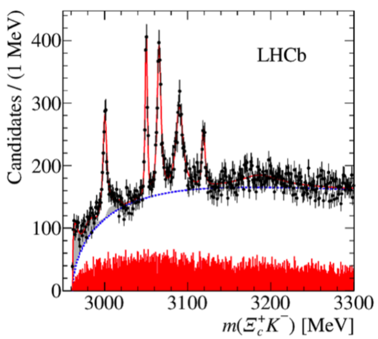


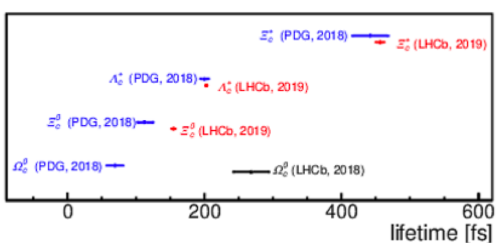


Charm @LHCb: A broad programme

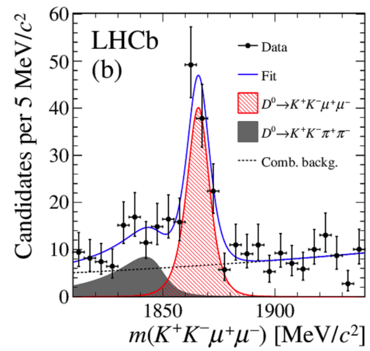
Spectroscopy, production, & properties

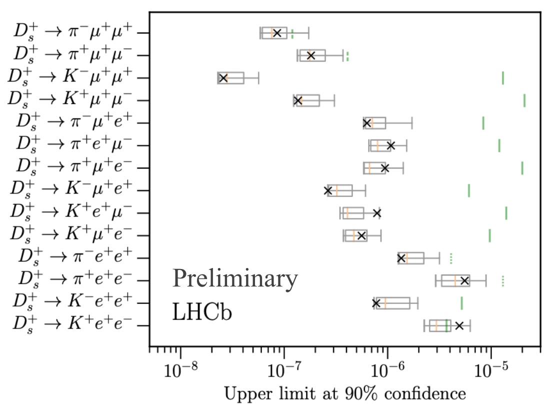




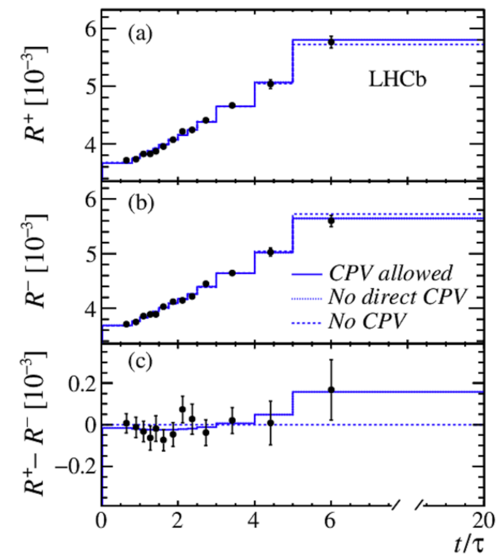


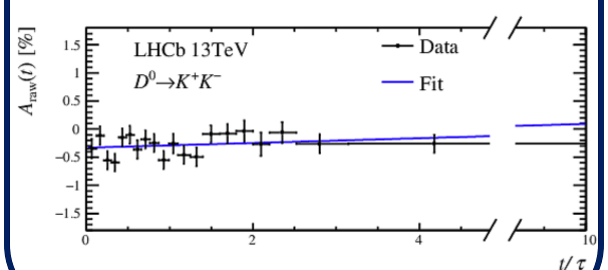
Rare charm decays





Mixing and CP violation

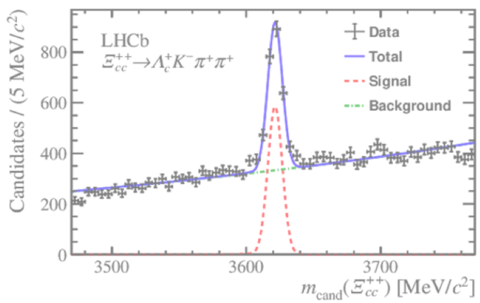


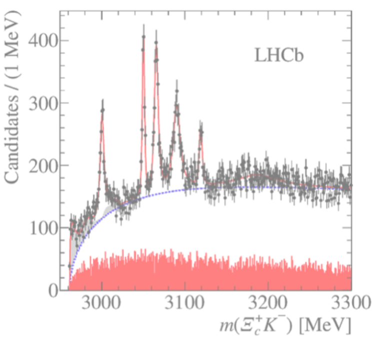


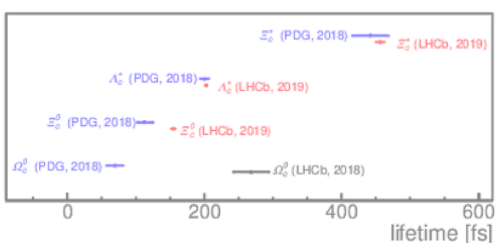
Charm @LHCb: A broad programme

RF7

Spectroscopy, production, & properties

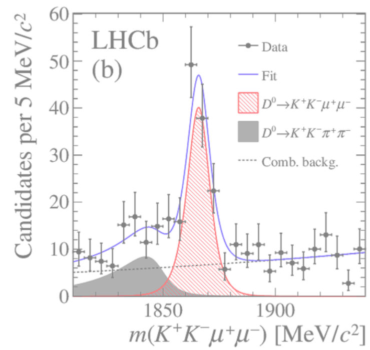


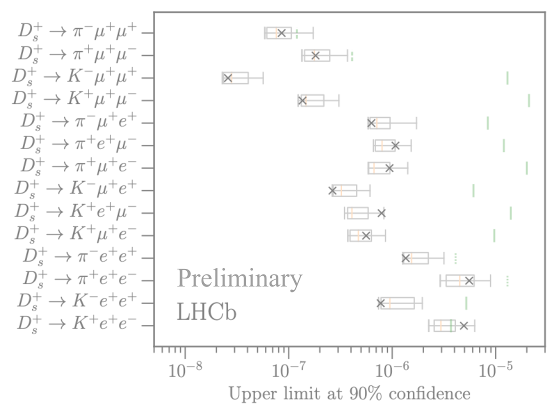




See Dominik Mitzel's talk

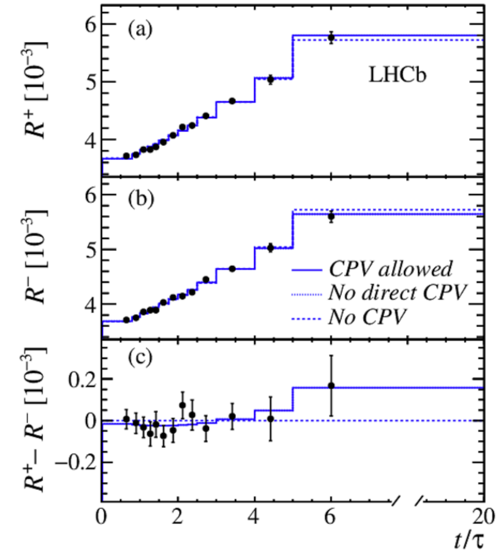
Rare charm decays

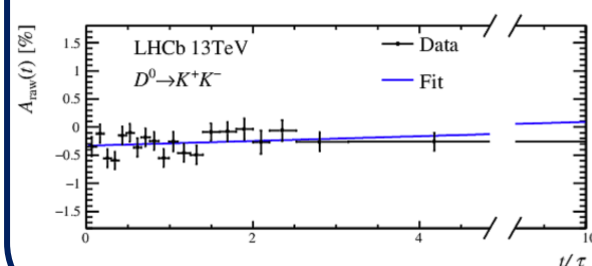




This talk

Mixing and CP violation





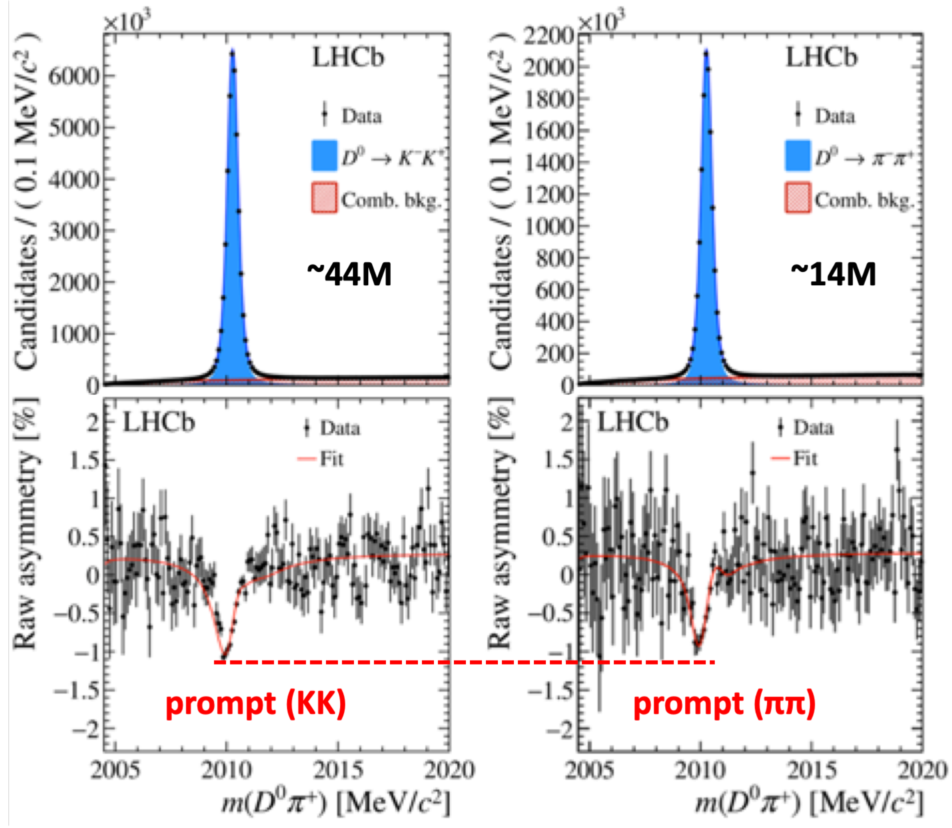
CPV in charm: the post-discovery era

Observation of *CP* violation in charm decays

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

Inconsistent with CP symmetry at >5σ level

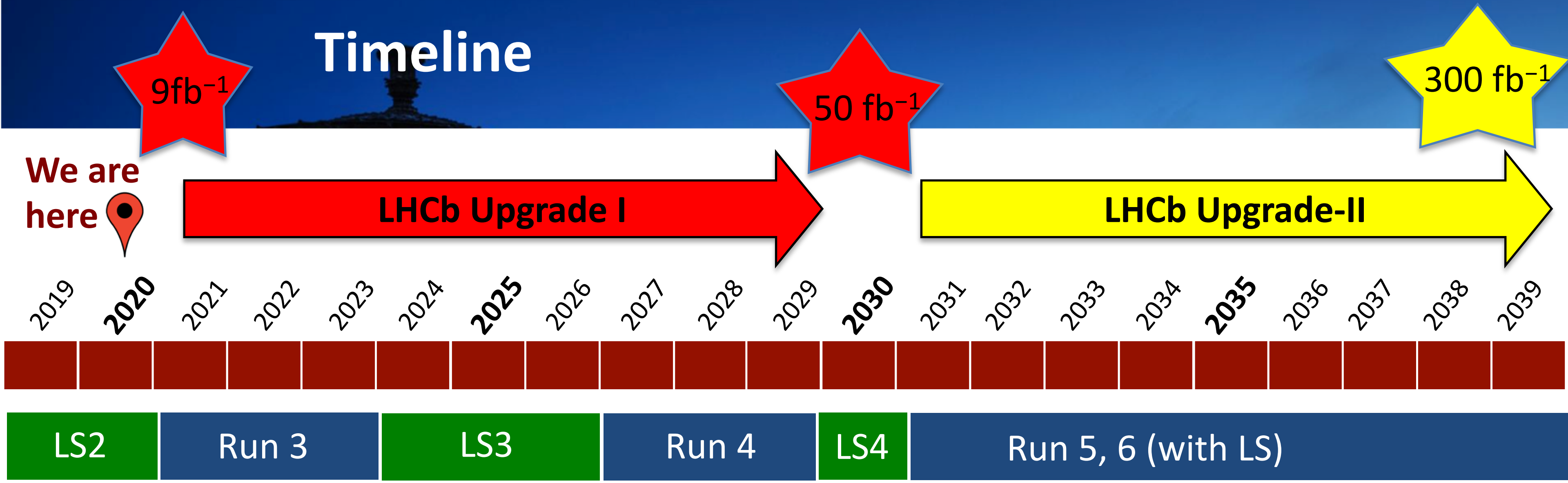
- Need full Run 1-2 sample to reach discovery sensitivity
- More data gives more precision… ($\sigma_{stat} \approx 3\sigma_{syst}$)
- SM or BSM?



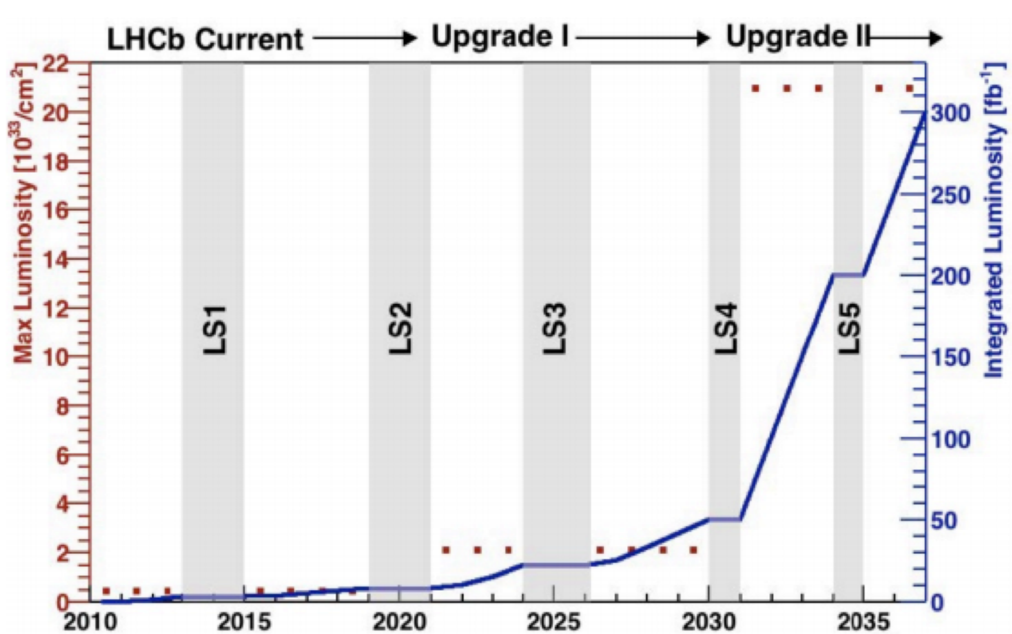
PRL 122 (2019) 211803

⇒ Must discover and measure CPV in other channels

Timeline



9fb^{-1}
50 fb^{-1}
300 fb^{-1}
We are here
LHCb Upgrade I
LHCb Upgrade-II
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
LS2
Run 3
LS3
Run 4
LS4
Run 5, 6 (with LS)



LHCb Current
Upgrade I
Upgrade II
Max Luminosity [10^{33}/cm^2]
Integrated Luminosity [fb^{-1}]
LS1
LS2
LS3
LS4
LS5
2010
2015
2020
2025
2030
2035

CP violation snapshot

	CPV in decay	Mixing-induced CPV
Two-body	**ΔA_{CP}**($D^0 \to hh$) and **A_{CP}**(hh): PRL 108 (2012) 111602 PLB 723 (2013) 33 JHEP 07 (2014) 041 PRL 116 (2016) 191601 PLB 767 (2017) 177 PRL 122 (2019) 211803 **$D_{(s)}^+ \to \eta'\pi^+$** PLB 771 (2017) 21 **$D^0 \to K_S^0 K_S^0$** JHEP 10 (2015) 055 JHEP 11 (2018) 048 **$D_{(s)}^+ \to K_S^0 h^+$** JHEP 06 (2013) 112 JHEP 10 (2014) 025 PRL 122 (2019) 191803	**$A_\Gamma(D^0 \to hh)$**: JHEP 1204 (2012) 129 (KK), **+y_{CP}** PRL 112 (2014) 041801 JHEP 04 (2015) 043 PRL 118 (2017) 261803 PRD 101 (2020) 012005 **y_{CP}(hh)**: PRL 122 (2019) 011802 **WS $D^0 \to K^+\pi^-$**: PRL 110 (2013) 101802 PRL 111 (2013) 251801 PRD 95 (2017) 052004 PRD 97 (2018) 031101
Multi-body	**$D^0 \to K^-K^+\pi^-\pi^+$, $\pi^-\pi^+\pi^-\pi^+$**: PLB 726 (2013) 623 (S_{CP}) JHEP 10 (2014) 005 (T-odd) PLB 769 (2017) 345 (energy test) JHEP 02 (2019) 126 (AmAn) **$D^+ \to K^-K^+\pi^+$** PRD 84 (2011) 112008 JHEP 06 (2013) 112 **$D^+ \to \pi^+\pi^-\pi^+$**: PLB 728 (2014) 585 **$\Xi_c^+ \to pK^-\pi^+$** (SCP, KNN) arXiv:2006.03145 (2020) **$D^0 \to \pi^+\pi^-\pi^0$** PLB 740 (2015) 158 **$\Lambda_c^+ \to ph^+h^-$** JHEP 03 (2018) 182	**$D^0 \to K_S^0\pi^+\pi^-$** JHEP 04 (2016) 033 (model-indep) PRL 122 (2019) 231802 (‘bin-flip’) **$D^0 \to K^-\pi^+\pi^-\pi^+$** PRL 116 (2016) 241801 https://lhcbproject.web.cern.ch/lhcbproject/Publications/p/LHCb-PAPER-2015-057.html

Future prospects: CPV in decay

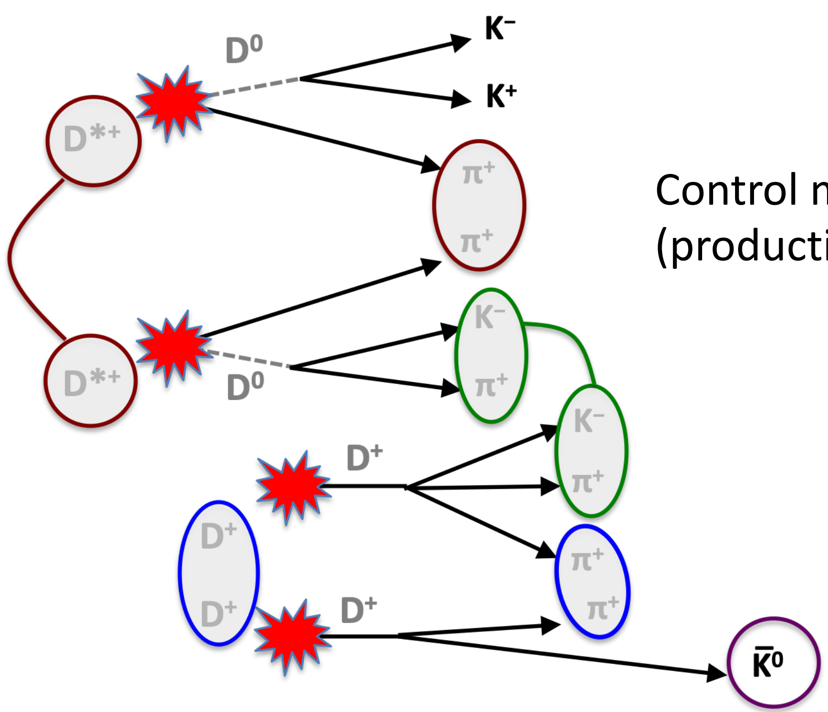
https://cds.cern.ch/record/2636441
"Physics case for an LHCb Upgrade II"

(1) ΔA_{CP} → individual $K^+K^-/\pi^+\pi^-$ asymmetries

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

Naively, $A_{CP}(KK) = -A_{CP}(\pi\pi)$
$\Rightarrow |A_{CP}| \approx 8 \times 10^{-4}$

Could reach 5σ sensitivity early in Run 5



Control modes to cancel nuisance asymmetries (production and detection)

Future prospects: CPV in decay

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⇒ $|A_{CP}| \approx 8 \times 10^{-4}$

Could reach 5σ sensitivity early in Run 5

Dominant uncertainties:

- **Kinematic reweighting**
  ⇒ Also reduces effective yield
- Contamination from **secondary charm** $pp \to H_b \to H_c$
  ⇒ Interplay between ability to suppress and understand residual effect
- Knowledge of **detector material**
  ⇒ Need accurate model in simulation and/or new data-driven approaches

Future prospects: CPV in decay

https://cds.cern.ch/record/2636441
"Physics case for an LHCb Upgrade II"

(2) Other two-body channels

Channel	σ_{stat} [A_{CP}] (Run 1-5)	σ_{stat} [A_{CP}] Latest	
$D^0 \to K_S^0 K_S^0$	28×10^{-4}	$\sim 120 \times 10^{-4}$	Projection for Run 1-2
$D^0 \to K_S^0 K^{*0}$	15×10^{-4}		
$D_s^+ \to K_S^0 \pi^+$	3.2×10^{-4}	17×10^{-4}	6.8fb^{-1} (70% of Run 1-2)
$D^+ \to K_S^0 K^+$	1.2×10^{-4}	6.1×10^{-4}	
$D^+ \to \phi \pi^+$	0.6×10^{-4}	4.0×10^{-4}	
$D_s^+ \to \eta' \pi^+$	3.2×10^{-4}	36×10^{-4}	3fb^{-1} (Run 1)

+ ongoing A_{CP} measurements with Run 1-2 data for:
- **$D_{(s)}^+ \to h^0 h^+$ [h^0: π^0,η]**
- **$D^0 \to V\gamma$ [V: ϕ,ρ]**

Run 3-5 will need:
- Improved **triggers** for K_S^0 candidates
- Better **neutral PID** (e.g. γ-π^0 separation)
- Where possible, **aligned selections** between signal and control modes

Future prospects: CPV in decay

https://cds.cern.ch/record/2636441
"Physics case for an LHCb Upgrade II"

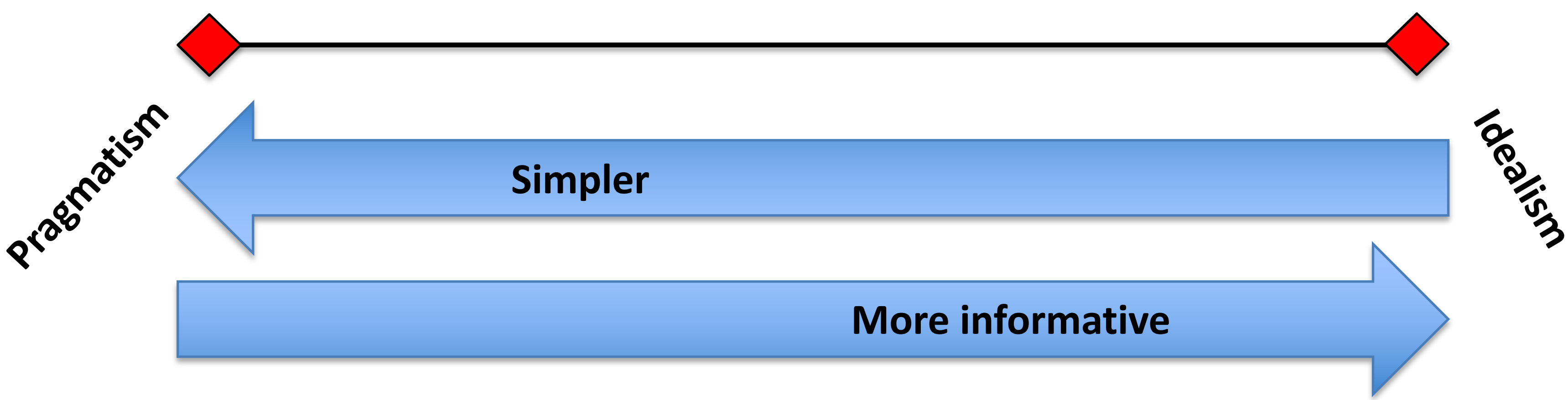
(3) Multibody final states

Search for 'phase-space localised' CPV driven by intermediate resonances
⇒ Successful in B sector, e.g. $B^+ \rightarrow \pi^+\pi^+\pi^-$

Range of techniques being used in LHCb, with different strengths

Simple statistical tests
e.g. binned asymmetry,
Nearest-neighbour,
Miranda method, Energy Test

Amplitude analysis:
Incorporate phase
variation in fit to data



Future prospects: CPV in decay

https://cds.cern.ch/record/2636441
"Physics case for an LHCb Upgrade II"

(3) Multibody final states

Amplitude analysis example ($D^+ \to \pi^- \pi^+ \pi^+$):
5σ sensitivity bounds on the phase difference (°) for main resonances

resonant channel	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$f_0(500)\pi$	0.30	0.13	0.083	0.032
$\rho^0(770\pi$	0.50	0.22	0.14	0.054
$f_2(1270)\pi$	1.0	0.45	0.28	0.11

'Energy Test' example ($D^0 \to \pi^- \pi^+ \pi^- \pi^+$):
3σ sensitivity bounds on magnitude and phase difference for main resonances

R (partial wave)	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$a_1 \to \rho^0\pi$ (S)	1.4%	0.6%	0.4%	0.17%
$a_1 \to \rho^0\pi$ (S)	0.8°	0.35°	0.24°	0.10°
$\rho^0\rho^0$ (D)	1.4%	0.6%	0.4%	0.17%
$\rho^0\rho^0$ (P)	0.8°	0.35°	0.24°	0.10°

Future needs:

Control over nuisance asymmetries to trust p-values

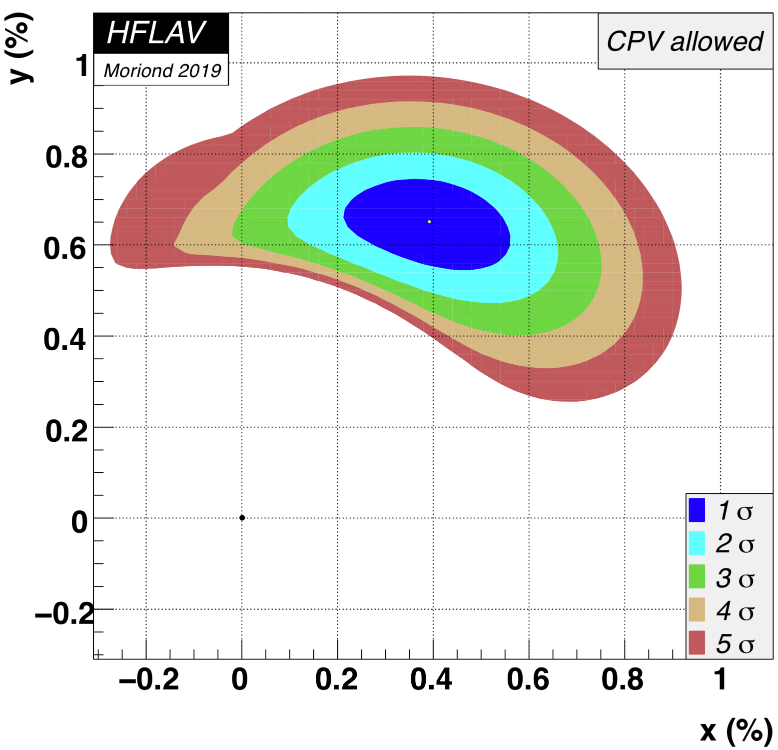
Improved amplitude models

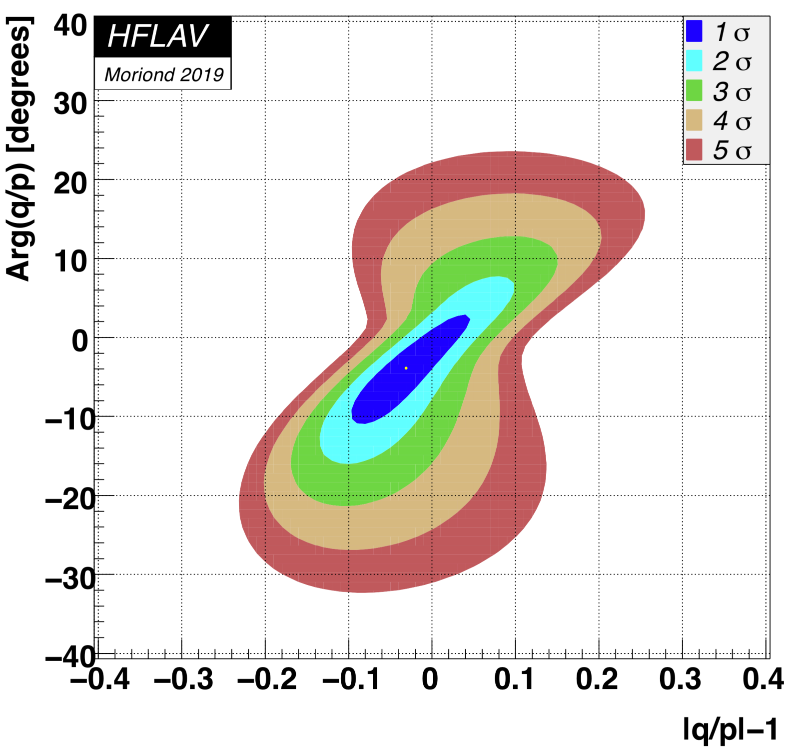
Methods which scale to very large data samples (e.g. GPUs), or clever techniques to reduce computation (e.g. arXiv:1801.05222)

Charm mixing and mixing-induced CPV

Next major discovery in charm (after ΔA_{CP}) could be mixing-induced CPV
⇒ Big challenge as mixing is so highly suppressed

Also yet to confirm non-zero mass difference (=x) at 5σ level

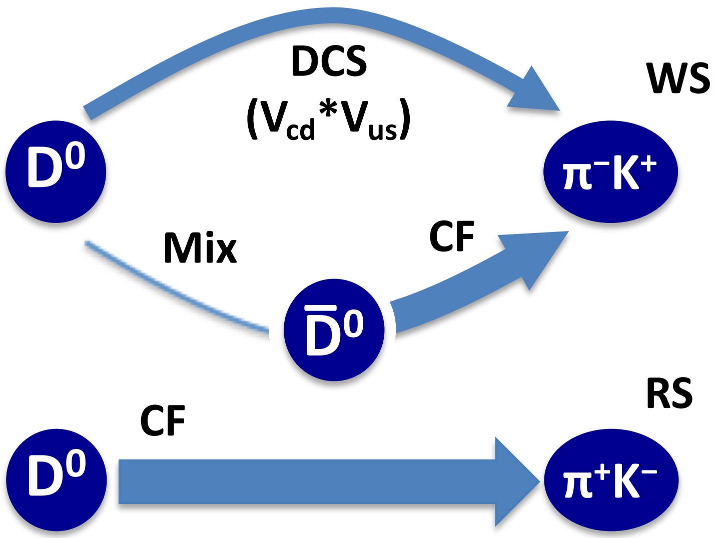




https://hflav-eos.web.cern.ch/hflav-eos/charm/

Charm mixing and mixing-induced CPV

(1) Wrong-sign $D^0 \to K^+\pi^-$



Mixing discovery mode, sensitive to CPV in mixing & interference (q/p) and in decay (A_D)

Currently: $\sigma_{stat} = 2\sigma_{syst}$

Leading systematics:

⇒ Flavour **tagging** (D*)

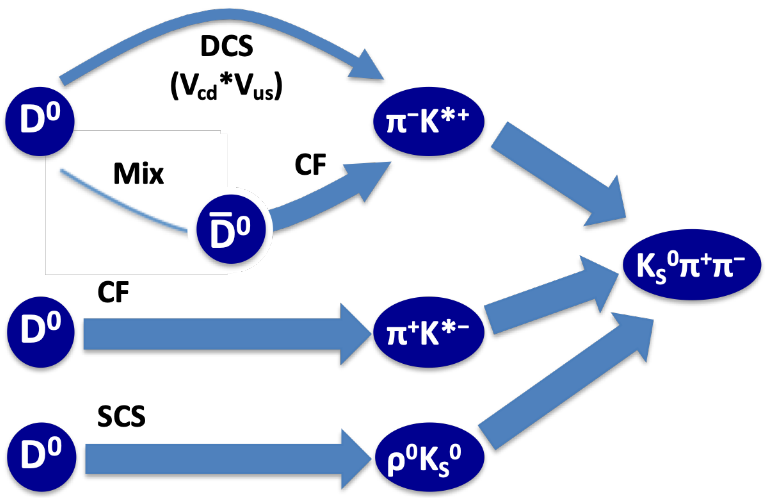
⇒ **Secondary** charm contamination

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(\lvert q/p \rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–3 (23 fb^{-1})	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1–4 (50 fb^{-1})	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1–5 (300 fb^{-1})	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

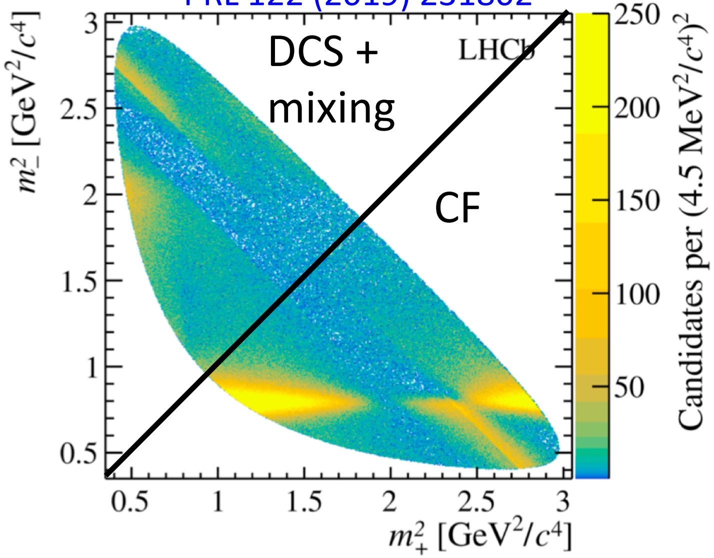
(Statistical uncertainties)

Charm mixing and mixing-induced CPV

(2) Golden mode $D^0 \to K_S^0\pi^+\pi^-$



PRL 122 (2019) 231802

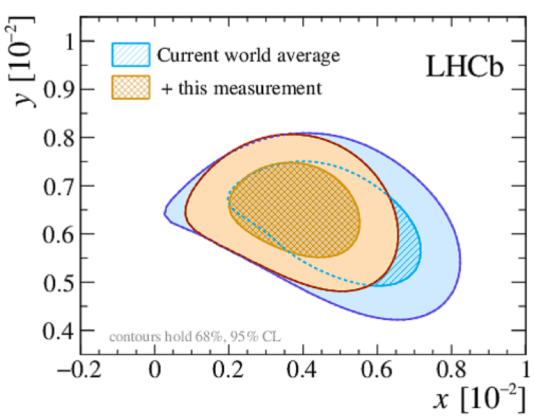


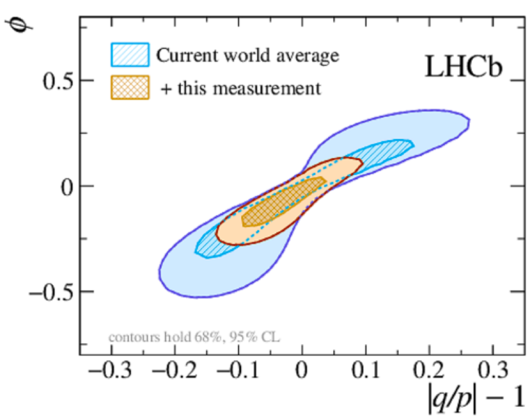
Time- and phase-space dependent analysis

Model-independent (using input from CLEO / BESIII) or amplitude analysis

Latest results (Run 1)

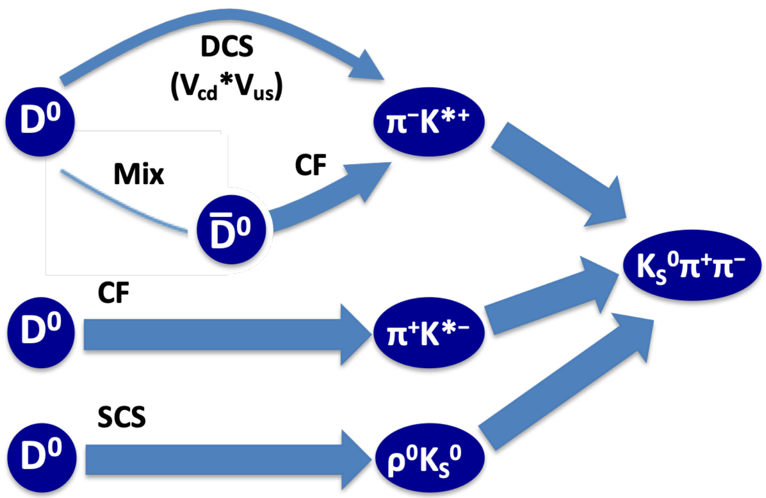
$\sigma_{stat} = (3-4)*\sigma_{syst}$





Charm mixing and mixing-induced CPV

(2) Golden mode $D^0 \to K_S^0\pi^+\pi^-$



Both promptly produced charm ($D^{*\pm}$-tagged) and from secondary B hadron decays (μ-tagged)

Major systematics:

- Detector acceptance / correlations
- Mistagged component (μ-tagged)
- Secondary contamination ($D^{*\pm}$-tagged)
- Precision of strong phase inputs (for model-independent approach)
- Choice of model (amplitude analysis)

⇓

All systematics are reducible, but will take care and effort.

Some reliance on simulation – need to ensure access to large and realistic samples

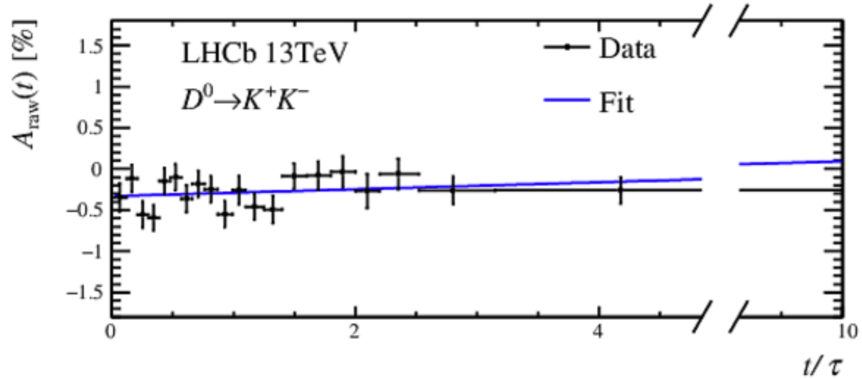
Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\|q/p\|)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

Charm mixing and mixing-induced CPV

(3) Time-dependent CPV: $A_\Gamma(D^0 \to h^+h^-)$

Most precise constraint on time-dependent CPV in charm (Run 1-2):

$A_\Gamma = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}$



Major systematics controlled by CF control channel in the same data [$D^0 \to K^-\pi^+$]
⇒ Stat limited for foreseeable future

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

(Not a) Summary

I didn't discuss:

- CPV in baryons
- Amplitude analyses – crucial input on QCD and nature of light states
- Lepton non-universality – just starting to explore in SL charm at LHCb
- Measurements of BRs, masses, lifetimes…
- Doubly-charmed baryons

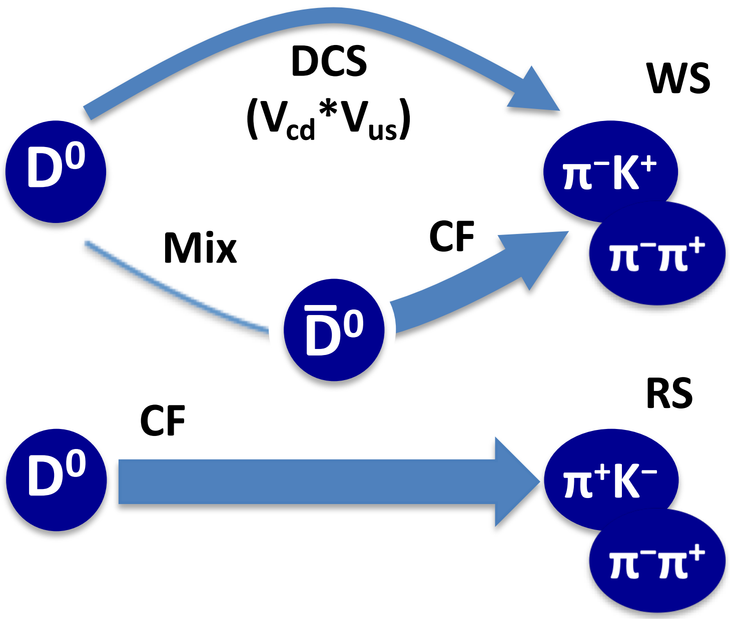
Key developments to watch in LHCb Run 3:

- A **new detector**. Better vertexing, tracking, and particle ID.
- Expanded use of **Turbo trigger**. Custom exclusive lines, custom persistence.
- More **fast simulation** (e.g. ReDecay, SplitSim) to save resources without sacrificing realism.

Thanks for your time

Charm mixing and mixing-induced CPV

(1a) Wrong-sign $D^0 \to K^+\pi^-\pi^+\pi^-$



Multibody extension of WS $D^0 \to K^+\pi^-$
⇒ offers even higher sensitivity to CPV
⇒ exploit strong phase variation over 5D PhSp

But more challenging
⇒ Model / constrain strong phase variation
⇒ Control efficiency variation over phase space and decay time (correlated)

Proof-of-principle analyses with Run 2 data now in progress

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'_{K\pi\pi\pi})$	$\sigma(y'_{K\pi\pi\pi})$	$\sigma(\lvert q/p \rvert)$	$\sigma(\phi)$
Run 1–2 ($9\,\mathrm{fb}^{-1}$)	0.22	2.3×10^{-4}	2.3×10^{-4}	0.020	$1.2°$
Run 1–3 ($23\,\mathrm{fb}^{-1}$)	1.29	0.9×10^{-4}	0.9×10^{-4}	0.008	$0.5°$
Run 1–4 ($50\,\mathrm{fb}^{-1}$)	3.36	0.6×10^{-4}	0.6×10^{-4}	0.005	$0.3°$
Run 1–5 ($300\,\mathrm{fb}^{-1}$)	22.5	0.2×10^{-4}	0.2×10^{-4}	0.002	$0.1°$

(Statistical uncertainties)